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HOW SPECIAL ARE BRIGHTEST CLUSTER GALAXIES? THE IMPACT OF NEAR-INFRARED LUMINOSITIES ON SCALING RELATIONS FOR BCGS

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ABSTRACT

Using the extended J, H and K magnitudes provided by the 2MASS data archive, we have considered the position of brightest cluster galaxies (BCGs) in the observed relations between supermassive black hole (SMBH) mass and the host galaxy properties, as well as their position in the stellar velocity dispersion and luminosity ($\sigma_* - L$) relation, compared to E and S0 galaxies. We find that SMBH masses ($M_\bullet$) derived from near-infrared (NIR) magnitudes do not exceed $\sim 3 \times 10^9 M_\odot$ and that these masses agree well with the SMBH mass predictions made from stellar velocity dispersions. In the NIR, there is no evidence that BCGs depart from the $\sigma_* - L$ relation defined by less luminous early-type galaxies. The higher SMBH masses predicted from V-band luminosities ($M_\bullet \lesssim 10^{10.5} M_\odot$) are attributed to the presence of extended blue envelopes around the BCGs.

Subject headings: galaxies: elliptical — galaxies: evolution — galaxies: fundamental parameters — galaxies: photometry

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1. INTRODUCTION

Whether the first galaxies were formed from initial large-scale condensations, or grew from an assembly of smaller bodies, still remains one of the most fundamental unanswered questions in modern astrophysics. We can place important constraints on these formation and evolutionary scenarios by studying the most massive galaxies. Similarly, formation and evolution conditions can be placed on supermassive black holes (SMBHs), as it is now well known that all galactic bulges harbor SMBHs at their centers (Ferrarese & Ford 2005) and that the properties of the host bulges correlate with the mass of the central SMBHs: the SMBH mass *vs.* bulge luminosity ($M_\bullet - L$) relation (Kormendy & Richstone 1995), the SMBH mass *vs.* stellar velocity dispersion ($M_\bullet - \sigma_*$) relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000), and the SMBH mass *vs.* concentration index relation (Graham et al. 2003).

As highly luminous massive galaxies found toward (or at) the centers of galaxy clusters, brightest cluster galaxies (BCGs) have received considerable interest. This interest is enhanced due to the recent release of data from extended sky surveys such as the SDSS (Adelman-McCarthy et al. 2006) and 2MASS (Jarrett et al. 2000). The surface brightness profiles (SBPs) of BCGs are well fit by the same Sersic (1968) law that describes less-luminous spheroids (Graham et al. 1996), apart from the outer-most regions which sometimes exhibit faint, extended envelopes (Oemler 1976; Bernardi et al. 2006). Furthermore, the BCGs appear to obey the same relations between fitting parameters that characterize E/S0 galaxies generally (Graham et al. 1996). Lauer et al. (2006a, hereafter L06) noted that the $M_\bullet - L$ relation, in the V band ($M_\bullet - L_V$), predicts higher SMBH masses in BCGs than are predicted by the $M_\bullet - \sigma_*$ relation, and used this observation to argue that BCGs are formed from dissipation-less mergers. Bernardi et al. (2006, hereafter B06) find similar results based on data from the C4 cluster catalog of Miller et al. (2005). The slope in the size-luminosity relation is found to be steeper in BCGs when compared to the bulk of E/S0's, and the σ_* *vs.* luminosity ($\sigma_* - L_R$) relation is seen to flatten for the brightest galaxies. This leads to a curvature in the fundamental plane (and possibly the $M_\bullet - \sigma_*$ relation).

While it is generally accepted that the $M_\bullet - \sigma_*$ relation shows less scatter than the $M_\bullet - L_V$ relation, and is therefore the preferred "secondary" SMBH mass estimation technique, it has been known for some time that the scatter in the relations become similar if bulge parameters are derived in the near-infrared (NIR) using two-dimensional image analysis (Marconi & Hunt 2003, hereafter MH03). With this in mind, and prompted by the interesting results for BCGs in the $M_\bullet - L_V$ and $\sigma_* - L_R$ relations, we have conducted a photometric study of BCGs based on the data contained within the 2MASS extended source catalog. In § 2 we give details about the treatment of the BCG sample and in § 3 we present the results, which are discussed in § 4. § 5 sums up.

2. THE SAMPLE

The 219 galaxies used here are taken from L06 where $\sim 30\%$ are BCGs and the remainder are E/S0's. This same sample has also recently been used to study the bi-modality of SBPs in early type galaxies (Lauer et al. 2006b). The L06 data includes the absolute V-band magnitudes (M_V) and, except in 51 cases, a value for σ_* (there are 33 BCGs with estimates of σ_*). The errors of 10% in M_V and σ_*, as quoted by L06, are adopted. We have supplemented the M_V data with the NIR data (J, H and K magnitudes, effective radii and surface brightnesses) contained within the 2MASS extended source catalog. All magnitudes were corrected for galactic extinction according to Schlegel et al. (1998). Distances were all adjusted to a common scale, with $H_0 = 70$ km s^{-1} Mpc^{-1}, and primarily taken from the surface brightness fluctuation survey of Tonry et al. (2001). Remaining distances were taken from Laine et al. (2003) or from the Virgo in-fall corrected recessional velocities

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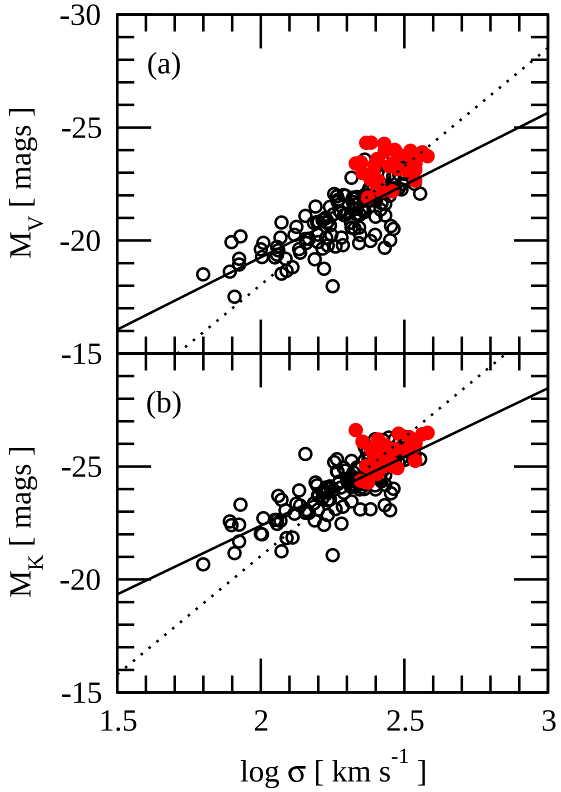

FIG. 1.— The relationship between σ_* and luminosity in the V-band (a) and K-band (b). Open black circles mark the position of E and S0's while filled red circles show BCGs. The solid lines show the fit to just the E/S0 populations, the dotted lines mark the fit of Bernardi et al. (2006) to the C4 BCG catalog.

listed by Hyperleda[3] (Paturel et al. 2003).

3. BCGS IN THE NIR

In Figure 1 we show the relationship between $\sigma_* - L_V$ and $\sigma_* - L_K$. In both cases we plot the best-fit relation as defined from the E/S0 galaxies (solid line) as well as the $\sigma_* - L_R$ fit given by B06 (their Figure 6). The B06 fit is given a color correction of V-R=0.7 and R-K=2.3. We find shallower slopes for the E/S0 population consistent with the B06 findings. Figure 1(a) demonstrates that the "bending" of the $\sigma_* - L_V$ relation, as noted by B06, is also seen in the L06 sample – BCGs fall above the relation defined by the E/S0's. In the NIR (Figure 1b) the BCGs do not define a clearly separate population as in Figure 1(a), instead they are distributed in the same fashion as the E/S0 galaxies. The typical offsets of the BCGs from the relation defined by the E/S0's are 1.20 mags in M_V and 0.48 mags in M_K, respectively.

The color corrections applied to the dotted lines in Figure 1 place the B06 fits to the C4 catalog nicely through the L06 BCG sample, but these are not necessarily the colors one may expect in early-type galaxies. For example, Idiart et al. (2002) and Grasdalen (1975) typically find V-R<0.6 and V-K>2.6 respectively. Until a complete photometric study of BCGs is executed, we will not be sure about their intrinsic colors (the Laine et al. (2003) sample only covered the I-band). However, it is comforting to note that the slopes of the B06 fits, which are consistent with previous results (e.g. Dressler et al. 1987), complement the BCG data.

[3] `http://leda.univ-lyon1.fr`

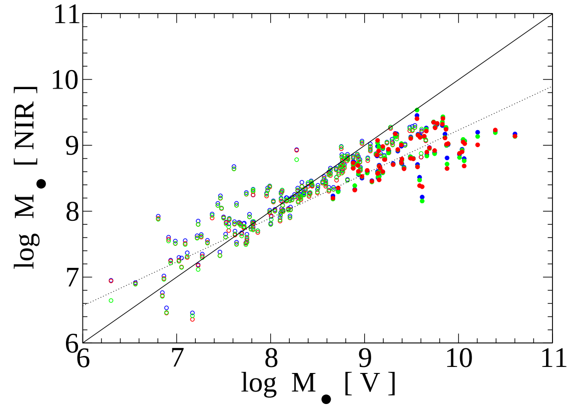

FIG. 2.— V-band *vs.* NIR $M_\bullet$ estimates. The solid line marks a one-to-one relation. Open circles are E/S0's, closed circles are BCGs. Blue, green and red colors refer to the J, H and K bands respectively. The dotted line marks the fit to all the K-band data.

Figure 2 demonstrates the relationship between $M_\bullet$ estimates from the V-band (hereafter $M_\bullet(V)$), using the relation as defined by L06 (their Equation 4), and $M_\bullet$ estimates from the NIR data (hereafter $M_\bullet(J,H,K)$), using the relations derived by MH03 (their Table 2, group 1 galaxies). Below $M_\bullet \approx 10^{8.5} M_\odot$ the agreement between the V and NIR bands is good, with the NIR relations predicting slightly more massive SMBHs with respects to the V relation. Above $10^{8.5} M_\odot$ all BCGs fall below the one-to-one relation; the NIR data predicts significantly smaller SMBH masses as we travel along the mass function, with no masses exceeding $10^{9.4} M_\odot$. The fit to the K-band relation is shown as a dotted line and has a slope of 0.6 (the slope is 0.7 for just the E/S0 population).

In order to check the validity of the 2MASS NIR magnitudes as surrogates for $M_\bullet$, we take the estimates as derived from both the $M_\bullet - L_V$ and $M_\bullet - L_{J,H,K}$ relations and plot them against 17 $M_\bullet$ estimates made from primary methods in early type galaxies (Figure 3 - *top row*). The scatter around the one-to-one lines is 0.16 in the NIR bands and 0.18 in the V-band. The best fits to the relations (dotted lines) show that, if extrapolated to $M_\bullet > 10^{10} M_\odot$, the $M_\bullet - L_V$ relation would tend to under-estimate $M_\bullet$, whereas the $M_\bullet - L_{J,H,K}$ relations would tend to over-estimate $M_\bullet$. In addition, Figure 3(e-h) shows how photometric $M_\bullet$ estimates compare to those predicted from the $M_\bullet - \sigma_*$ relation. $M_\bullet$ estimates are derived from the $M_\bullet - \sigma_*$ relation (hereafter $M_\bullet(\sigma_*)$) defined by Tremaine et al. (2002). In Figure 3(e) the $M_\bullet - L_V$ relation (above $10^{8.5} M_\odot$) predicts SMBH masses greater than those expected from the $M_\bullet - \sigma_*$ relation. However, in the NIR, this observation is not made; the J, H and K mass predictions are consistent with estimates from the $M_\bullet - \sigma_*$ relation. The $M_\bullet - L_V$ relation forecasts SMBH masses up to $\sim 2.5 \times 10^{10} M_\odot$, whereas the NIR relations do not produce SMBH masses above $\sim 2.8 \times 10^9 M_\odot$. It is also noted that the scatter in the $M_\bullet(J,H,K) - M_\bullet(\sigma_*)$ relations are significantly less than the $M_\bullet(V) - M_\bullet(\sigma_*)$ relation.

We are confident that the $M_\bullet$ estimates from the $M_\bullet - L_{J,H,K}$ relations (in the range $10^{7.4} - 10^{9.3} M_\odot$) are as good (or better) than those mass estimates made from the $M_\bullet - L_V$ relation, i.e., Figure 3(a-d). We do note, however, that neither relation has been calibrated considering BCGs. In Figure 2 we see that the slope of the relation between $M_\bullet(V)$ and $M_\bullet(J,H,K)$ is offset from

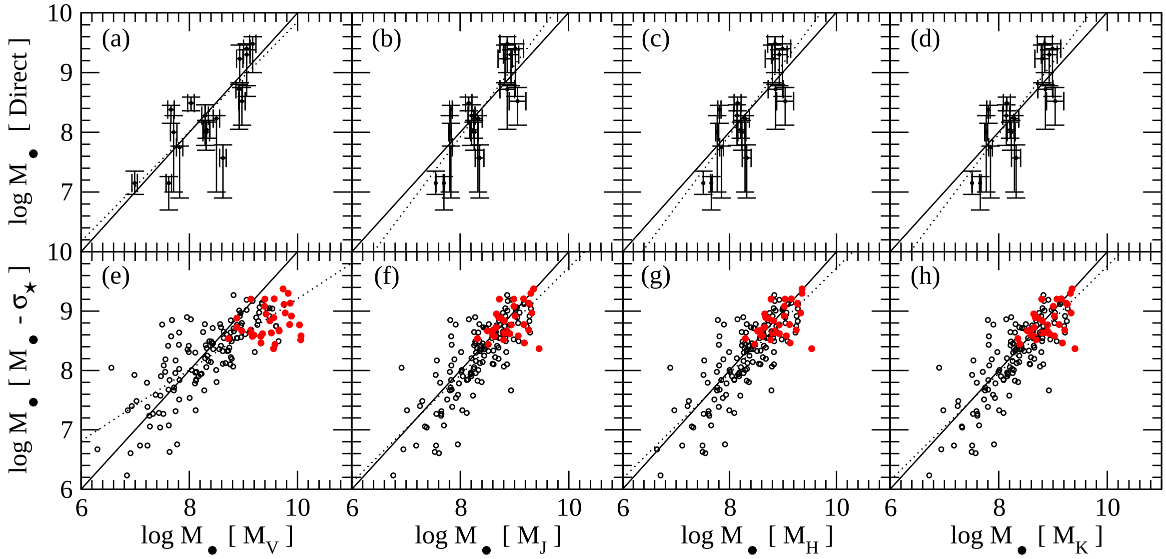

FIG. 3.— Comparing photometric $M_\bullet$ estimates with direct and $M_\bullet - \sigma_*$ estimates. [*Top row*] V, J, H and K masses compared to direct estimates. [*Bottom row*] V, J, H and K masses compared to $M_\bullet - \sigma_*$ estimates. Open black circles are E/S0's, BCGs are filled red circles. In all cases the solid line represents a one-to-one relation and the dotted lines show the best fit relation.

the one-to-one relation. This would result if the slope of either the NIR or V-band relation were erroneous. Since $M_\bullet(J,H,K)$ and $M_\bullet(\sigma_*)$ agree well, i.e., Figure 3(f-h), we must accept the error is with the $M_\bullet - L_V$ relation. The discrepancy is reduced if we assume that the slope in the $M_\bullet - L_V$ relation is the same as the one reported by MH03.

4. DISCUSSION

BCGs do not appear to be "special" when viewed at NIR wavelengths. They follow the same $\sigma_* - L_K$ distribution as defined by less luminous spheroids, and comparable masses are predicted for the SMBHs in BCGs based either on velocity dispersions or on total magnitudes.

We now explore possible reasons for the observed discrepancies between the results in the NIR and V-bands. Naively, either the NIR magnitudes are under-estimated or the V-band magnitudes are over-estimated. The distances to the BCGs in the sample frequently exceed 100 Mpc and top out at ~ 280 Mpc. Consequently, a proportion of the intrinsic apparent SBPs of these BCGs could be below the sensitivity limit of the 2MASS survey, leading to an under-estimation of the total NIR magnitude. A relation between the flux of an object and its distance would indicate a background issue. However, we find a constant distribution of NIR fluxes with distance, i.e., no evidence for incomplete photometry.

The case of NIR and V-band under- and over-estimations in BCGs could be resolved by considering the faint extended luminous halos known to surround the most massive galaxies (Oemler 1976). The signature of such halos is an inflection in the SBPs at large r. B06 find that BCG galaxies in the C4 catalog form two classes, one in which the SBPs are well fit by de Vaucouleur's law and one with positive deviations at large r. In the NIR, the total magnitudes could be missing the contributions from faint halos or, luminosities are exposed to halo light in the V-band, the inclusion of which leads to an over-estimate of the total optical magnitude.

In order to include only bulge light, MH03 calibrated the $M_\bullet - L_{J,H,K}$ relations based on two-dimensional fitting to 2MASS profiles. The NIR magnitudes used here come from 2MASS apertures that may not reach out into the faint extended halos; they could again be under-estimated. For the $M_\bullet - L_{J,H,K}$ relation to predict a population of $10^{10} M_\odot$ SMBHs, i.e., for the BCGs to fall on the one-to-one relation in Figure 2, 2MASS photometry would have to be increased, on average, by 1.65 mags. This offset would need to vary with $M_\bullet$ and have no effect at masses below $10^{8.5} M_\odot$, where the results between $M_\bullet - L_V$ and $M_\bullet - L_{J,H,K}$ are consistent. We have checked the 2MASS photometry against the photometry published by MH03. Above $M_{J,H,K} \approx -25.5$ there is a systematic offset of ~ 0.4 mags corresponding to a shift in the $M_\bullet - L_{J,H,K}$ zero-point of $1.8 \times 10^7 M_\odot$. This is well within the errors of $M_\bullet$ estimates above $10^9 M_\odot$ and can be accounted for by different measurement techniques, as shown by our extensive simulations. A population of model galaxies, with parameters covering the ranges defined by the sample, were generated using `GALFIT` (Peng et al. 2002) and included the appropriate binning, PSF, noise characteristics and measurement techniques for extended sources in the 2MASS survey (Jarrett et al. 2000). The model SBPs were then integrated over the total radius and the radius defined by the 20 mag/arcsec^2 level. In over one thousand realizations, the mean difference between the "true" magnitude, and the one that would be measured by 2MASS, was $0.25(-0.2, +0.4)$ at the 1σ level, i.e., 2MASS magnitudes are mildly under-estimated. This is consistent with the difference between 2MASS magnitudes and MH03 magnitudes, and is significantly lower than the error required for 2MASS magnitudes to predict a population of $10^{10} M_\odot$ SMBHs.

It would be highly coincidental to find that NIR light missed in extended halos would serve to align the high mass ends of the $M_\bullet(\sigma_*) - M_\bullet(J,H,K)$ relation for BCGs. Photometry from further toward the blue end of the spectrum may be deep enough to include a significant contribution from these extended halos, leading to an increase in the estimation of BCGs luminosities and a turn-over in $M_\bullet$ estimates above a certain threshold.

Laine et al. (2003) provided the V-band magnitudes for the L06 study, where considerable effort was made to include the contributions from extended halos by integrating corrected R-band best fitting de Vaucouleurs profiles to infinity. In any case, since the extended halos sit in the overall cluster potential, they are unlikely to be related dynamically to the central regions in which σ_* is typically measured.

The inconsistent apertures used for the V and NIR magnitudes makes it difficult to directly compare BCG colors in order to make deductions on the possible nature of extended halos. However, based on the discussions above, we are lead to surmise that BCGs have blue envelopes, and that these envelopes increase V-band magnitudes to give excessive $M_\bullet$ estimates. This suggestion is supported by the BCG imaging survey of Patel et al. (2006), for example, who see decreasing B-R colors with increasing radius, by the observation that ellipticals show color gradients that become bluer with radius (Peletier et al. 1990) and the fact that cD radio galaxies are bluer than normal ellipticals (Véron-Cetty et al. 2000).

While we have shown that BCGs are not "special" in terms of their $\sigma_* - L_K$ distribution, nevertheless, their extreme luminosities and unique locations at the centers of galaxy clusters suggest special formation processes. It has long been argued that the extended envelopes of BCGs are debris from tidally-stripped galaxies, and hence that they are associated more closely with the overall cluster potential well than with any single galaxy (Merritt 1984a). The envelopes may also consist in part of stars formed in cooling flows (Fabian 1994). The presence of multiple nuclei in some BCGs argues in favor of these galaxies not being fully relaxed (Merritt 1984b). A photometrically complete, high-resolution imaging survey of BCGs would be able to provide a framework for a more quantitative analysis of these fundamentally important objects.

5. CONCLUSIONS

Brightest cluster galaxies offer the chance to study the pinnacle of galaxy evolution. They also give us the opportunity to study the top of the SMBH food chain by using the observed relations between $M_\bullet$ and the properties of the surrounding host galaxy. Taking data from the 2MASS archive, we have used a sample of BCGs to find that the relations between NIR luminosities and $M_\bullet$ predict an upper mass limit of $\sim 3 \times 10^9 M_\odot$. This is consistent with the most massive SMBH directly modeled at the center of M87 (Macchetto et al. 1997). We also find that, across all values, SMBH masses predicted from the NIR are consistent with those masses predicted from σ_*. In addition, we have shown that BCGs follow the same distribution, as defined by E/S0 galaxies, in the $\sigma_* - L_K$ relation. These finding have important implications for the nature of the SMBH mass function, and, as in the past, show that NIR data are to be preferred when estimating $M_\bullet$. While BCGs do not seem to be special, in the sense of hosting luminosity-derived hypermassive black holes or by defining a distinct population in the $\sigma_* - L_K$ plane, they may be interesting by virtue of being surrounded by extended faint blue halos. The unique local BCG environment, deep within a cluster potential, could be the driver of these halos, which may be populated by young stars tidally stripped from other cluster members or that are the results of intra-cluster gas accretion or other recent merger events.

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REFERENCES

Adelman-McCarthy, J. K., et al. 2006, ApJS, 162, 38
Bernardi, M., et al. 2006, submitted (astro-ph/0607117)
Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R., & Wegner, G. 1987, ApJ, 313, 42
Fabian, A. C. 1994, ARA&A, 32, 277
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Ferrarese, L., & Ford, H. 2005, Space Science Reviews, 116, 523
Gebhardt, K., et al. 2000, ApJ, 539, L13
Graham, A., Lauer, T. R., Colless, M., & Postman, M. 1996, ApJ, 465, 534
Graham, A. W., Erwin, P., Caon, N., & Trujillo, I. 2003, Revista Mexicana de Astronomia y Astrofisica Conference Series, 17, 196
Grasdalen, G. L. 1975, ApJ, 195, 605
Idiart, T. P., Michard, R., & de Freitas Pacheco, J. A. 2002, A&A, 383, 30
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S., Skrutskie, M., & Huchra, J. P. 2000, AJ, 119, 2498
Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581
Laine, S., van der Marel, R. P., Lauer, T. R., Postman, M., O'Dea, C. P., & Owen, F. N. 2003, AJ, 125, 478
Lauer, T. R., et al. 2006a, submitted (astro-ph/0606739)
Lauer, T. R., et al. 2006b, submitted (astro-ph/0609762)
Macchetto, F., Marconi, A., Axon, D. J., Capetti, A., Sparks, W., & Crane, P. 1997, ApJ, 489, 579
Marconi, A., & Hunt, L. K., 2003, ApJ, 589, L21
Merritt, D. 1984a, ApJ, 276, 26
Merritt, D. 1984b, ApJ, 280, L5
Miller, C. J., et al. 2005, AJ, 130, 968
Oemler, A., Jr. 1976, ApJ, 209, 693
Pahre, M. A., Djorgovski, S. G., & de Carvalho, R. R. 1998, AJ, 116, 1591
Patel, P., Maddox, S., Pearce, F. R., Aragón-Salamanca, A., & Conway, E. 2006, MNRAS, 370, 851
Paturel, G., Petit, C., Prugniel, P., Theureau, G., Rousseau, J., Brouty, M., Dubois, P., & Cambrésy, L. 2003, A&A, 412, 45
Peletier, R. F., Davies, R. L., Illingworth, G. D., Davis, L. E., & Cawson, M. 1990, AJ, 100, 1091
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sersic, J. L. 1968, Cordoba, Argentina: Observatorio Astronomico
Tonry, J. L., Dressler, A., Blakeslee, J. P., Ajhar, E. A., Fletcher, A. B., Luppino, G. A., Metzger, M. R., & Moore, C. B. 2001, ApJ, 546, 681
Tremaine, S., et al. 2002, ApJ, 574, 740
Tundo, E., et al. 2006, submitted (astro-ph/0609297)
Véron-Cetty, M.-P., Woltjer, L., Staveley-Smith, L., & Ekers, R. D. 2000, A&A, 362, 426